Flexible evaluation of complex equipment assembly cell

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ABSTRACT

Industry 4.0 has a huge impact on discrete manufacturing industry. The fierce market competition has expanded to the global scope, which also brings a series of unpredictable "turbulence" factors such as order diversity and market demand changes. Manufacturing enterprises can not only rely on product cost and quality to win, but also need to have the ability to meet the needs of users with the fastest response speed under the unpredictable environment, that is, the flexibility of the system. Based on the development trend of manufacturing system, this paper tries to establish a new method for quantitative evaluation of manufacturing system flexibility.

Keywords: Complex equipment, Cell production, Flexibility evaluation

1. INTRODUCTION

In order to measure the flexibility level of complex equipment assembly cell, this paper evaluates the flexibility of complex equipment assembly cell. On the basis of previous studies, this paper firstly summarizes and analyzes the factors that affect the flexibility of complex equipment assembly cells, and then designs the evaluation indexes of flexibility, including the performance indexes, efficiency indexes and conversion cost indexes of assembly cells, and selects appropriate characterization objects for each index. The flexibility level of complex equipment assembly cell is evaluated by calculating related indexes.

2. ANALYSIS OF FACTORS AFFECTING THE FLEXIBILITY OF ASSEMBLY CELL

The flexibility of production system is an important index to measure whether a manufacturing enterprise can cope with the external market changes quickly. Wang[1] believed that the flexibility could be evaluated by the efficiency of processing equipment of the production system, allowing the processing equipment to process a certain task, and calculating the flexibility of the production system according to the efficiency of the processing equipment to complete the task. Zhao[2] studied the flexibility of processing equipment. He believed that the flexibility of equipment would have an impact on the flexibility of the entire production system. A higher degree of flexibility of equipment represented a higher level of flexibility of the entire manufacturing system. Gong[3] takes the overall efficiency of the production system as the index to evaluate the flexibility of the processing cell. He believes that production systems with higher levels of flexibility are better able to cope with external changes. Zhou[4] believes that the assessment of flexibility can be measured by the lead time deviation. Ren[5] believes that the degree of flexibility of manufacturing systems can be evaluated by the economic losses caused by changes in market conditions. Morgan Swink[6] believes that the deviation between the planned delivery time and the actual delivery time of the order can be used as the performance index of the production system to evaluate its flexibility level. Hvolby[7] believes that the two indicators that enterprises pay most attention to are delivery time and product quality level, which can be used as evaluation indicators of flexibility.

Combined with previous studies, the production system's ability to deal with customer demands, the efficiency of processing equipment, and the ability to cope with external changes can reflect the flexibility of the production system. Starting from these three aspects, this paper designs corresponding evaluation indexes to evaluate the flexible processing cell of compressor blades.

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(1) Performance index of compressor blade flexible processing cell. The performance indicators can reflect the ability of processing cells to deal with customer demands stably, including the processing switching time of different kinds of products, the production cycle of products, the delivery time of customer orders, etc.

(2) Efficiency index of compressor blade flexible processing cell. The efficiency index reflects the resource utilization efficiency of the processing cell, including the running time of the equipment, the global equipment efficiency, etc. The efficiency index measures the reasonable allocation and application of resources by the processing cell. It can reflect the overall efficiency of the whole processing cell by calculating the OEE of key equipment.

(3) The conversion cost index of compressor blade flexible processing cell. Reflect is to cope with the changing market demand, processing cell to personnel, equipment and other costs to make changes.

Therefore, this study selects the performance index, efficiency index and conversion cost index of assembly cell to evaluate the flexibility of complex equipment assembly cell.

3. EVALUATION INDEX OF ASSEMBLY CELL FLEXIBILITY

3.1 Performance index of assembly cell

If a production system is more flexible, it will be able to handle customer orders in a timely manner, and the delivery deviation time is very small. Therefore, the flexibility level of the assembly cell can be expressed as a very stable order processing capacity of the processing cell. It can meet customers' orders of various varieties and small batches in time, and consume less time and capital. Therefore, in this study, order lead time deviation was used to evaluate the performance of processing cells.

Complex equipment assembly cell needs to process different types of orders within a certain period of time, and its expression is as follows:

$$Z = \{P_1, P_2, P_3, ..., P_n\} \tag{1}$$

$$P_n = \{D_1, D_2, D_3, ...D_n\} \tag{2}$$

Where Z represents the total orders received by the assembly cell within a period of time, P represents the types of products to be processed by the blade processing cell, and D represents the orders of different types of products.

The delivery time T of the customer order can be calculated by the following formula:

$$T = \sum_{n=1}^{N} (t_{an} + t_{bn} + t_{cn} + t_{dn}) + \sum_{n=1}^{N-1} t_{ey} + \sum_{f=1}^{F} t_f \tag{3}$$

Where N represents the number of processing equipment, t_a represents the average processing time of the cell to customer orders, t_b represents the waiting time in the production process, t_c represents the die changing time in the production process, t_d represents the processing time in the production process, t_e represents the transportation time in the production process, t_f represents the inspection time in the production process.

The calculation method of the planned order delivery time is the same as that of the actual order delivery time *T*. The relevant formulas given below with "*j*" subscript all represent the calculation formula under the planned state, and the calculation method is the same as that of the actual state.

The difference between the planned delivery time and the actual delivery time of different kinds of products $\Delta T = T_j - T$ is the delivery time deviation of the order. If the degree of flexibility of the assembly cell is relatively high, the calculated delivery time deviation will be relatively low, which indicates that the actual delivery time will be very close to the planned delivery time. Therefore, the size of the lead time deviation can reflect the flexibility level of the assembly cell. FIG.1 uses the bell density function of normal distribution to describe I to V different flexible states. Curves I and II show that under these two states, the mean value of the delivery time deviation of the order is the same, which can better complete the order task, but the variance of the delivery time deviation of state I is smaller than that of state II. Therefore, I is more stable than state II in processing different order demands and has a higher flexibility level than state II. The variances of delivery time deviations of III, IV and V are the same, and the delivery time deviations of state III are less than zero, indicating that the order task cannot be timely completed in this state, while the order task can be timely completed in state IV and V. However, the mean deviation of delivery time in state V is greater than zero, which indicates that there is a certain degree of waste in the production system's capacity in state V[8].

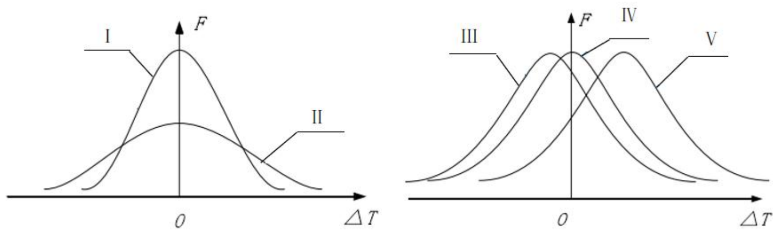

Figure 1. Bell density function of assembly cell performance.

In order to calculate the performance index of assembly cells under different flexible states, the dispersion degree of the deviation of order delivery time is expressed by *G**, and its calculation formula is shown in Formula (4) and (5), where *G* represents the coefficient of variation, *G** represents the normalized coefficient of variation, *n* represents different types of production orders, u is the average deviation of order delivery time, σ is the standard deviation of order delivery time.

$$G = \frac{\sigma}{u} \tag{4}$$

$$G^{*} = \frac{\sigma}{u}\frac{1}{\sqrt{n}} = \frac{\sigma}{u\sqrt{n}} \tag{5}$$

The value of *G** is used as the performance index of assembly cell to measure the ability of processing cell to handle customer demand. When the mean deviation of the order delivery time is greater than zero, the smaller the value of *G* at this time, the stronger the ability of the processing cell to process customer orders; On the contrary, if the value of *G* is larger, it indicates that the flexibility of the assembly cell is insufficient, resulting in the delay of the order delivery time. If the coefficient of variation *G* is negative, it means that the flexibility level of the assembly cell under the current state is not enough to cope with the changeable market demand.

In summary, under the premise that the mean delivery deviation is greater than zero, the lower the coefficient of variation *G*, the higher the performance of the assembly cell. The normalized variation coefficient *G** can reflect the performance of the assembly cell, and then show the flexible state of the system.

3.2 Efficiency index of assembly cell

The efficiency index reflects the resource utilization efficiency of assembly cell, which of the production system can be calculated by the global equipment efficiency of the production system. The traditional method obtains the OEE of the equipment by collecting the operating data of the equipment, but the OEE of a single device cannot measure the progress of the entire production system. Goldratt's constraint theory analyzed from the perspective of the whole production system. In this paper, the efficiency index of the assembly cell is determined by calculating the OEE of the key equipment[9].

$$OEE = F \cdot I \cdot K \tag{6}$$

$$OEE_j = F_j \cdot I_j \cdot K_j \tag{7}$$

Where, OEE is the actual global equipment efficiency, OEE_j is the planned global equipment efficiency, *F* is the time start-up rate of key equipment, *I* is the performance start-up rate of key equipment, and *K* is the qualified rate of the output product of the assembly cell.

OEE is an effective tool to evaluate the efficiency of production system. The efficiency coefficient of assembling cell equipment is calculated as follows:

$$\varepsilon = \frac{OEE_j - OEE}{OEE} \quad (8)$$

Efficiency coefficient can be used as a quantitative index to evaluate the efficiency of assembly cell. If it is greater than zero, it means that the actual efficiency of the assembly cell has not reached the planned efficiency, and the lower it is, the closer the actual efficiency of the assembly cell is to the planned efficiency. If it is less than zero, although the actual efficiency of the assembly cell at this time exceeds the planned efficiency, it actually reflects the insufficient control of the flexibility of the assembly cell.

3.3 Conversion cost index of assembly cell

In addition to the performance index and efficiency index, it is necessary to evaluate the flexibility level of assembly cell and calculate the cost of adjusting assembly cell to meet the changing market demand. A higher level of flexibility means faster response to customer orders. The higher the flexibility level of the assembly cell, the lower the cost of state transition. Therefore, the cost conversion index can be used to evaluate the degree of flexibility of the assembly cell and reflect the dynamic strain capacity of the flexibility of the assembly cell[10].

The conversion cost coefficient of the assembly cell to cope with the changing external market demand is calculated as shown in Equations (9)- (11) :

$$E_t = \frac{Q_t}{D_t} \quad (9)$$

$$P_t = \frac{J_t}{D_t} \quad (10)$$

$$C_1 = E_t \times P_t \quad (11)$$

E_t represents the utilization coefficient of equipment within time t; Q_t represents the number of equipment put into use within time t; D_t represents the number of product types produced within time t; P_t represents the utilization coefficient of personnel within time t; J_t represents the number of personnel involved in processing operations within time t; C_1 represents the resource conversion cost coefficient within time t.

The resource coefficient S is calculated using the actual conversion cost coefficient and the planned conversion cost coefficient as follows:

$$S = \frac{C_{1j} - C_1}{C_1} \quad (12)$$

In order to represent the process conversion cost required by the assembly cell to complete the composite product, the process conversion cost coefficient C_2 is calculated as shown in Equation (13).

$$C_2 = \frac{C(L_1,\ L_2,\ldots,\ L_n)}{C(L_1) + C(L_2) + \ldots + C(L_n)} \quad (13)$$

$C(L_1,\ L_2,\ldots L_n)$ represents the total cost of the combined product $L_1,\ L_2 \ldots L_n$ to complete the processing within t, and $C(L_i)$ represents the cost of the product L_i produced by the enterprise alone to complete the production and processing within t.

Then the flow coefficient Z can be calculated as shown in Equation (14) :

$$Z = \frac{C_2^* - C_2}{C_2} \quad (14)$$

Then, the conversion cost coefficient C of composite products produced in the complex equipment assembly cell period t can be calculated by taking the average of resource coefficient S and flow coefficient Z:

$$C = \frac{S + Z}{2} \quad (15)$$

The conversion cost of complex equipment assembly cell can be evaluated by using conversion cost coefficient C as a quantitative index. The value of conversion cost coefficient C is less than zero, indicating that the actual cost of state transition is greater than the planned cost. On the contrary, if C is greater than zero, it means that the actual cost of state transition is less than the planned cost. At this time, the larger the value of C, the lower the cost of completing state transition.

4. FLEXIBLE EVALUATION OF COMPLEX EQUIPMENT ASSEMBLY CELL

4.1 Calculation of performance index of assembly cell

In order to evaluate the overall flexibility level of the assembly cell, this paper collected demand orders as shown in Table1.

Table1. Lead time deviation data

Product name	Demand quantity	Delivery time deviation
A	500	343
B	600	247
C	360	162
D	200	108
E	300	124
F	1000	381
G	1200	406
H	500	217

According to Table 1, the average deviation and standard deviation of delivery deviation of customer orders in this month can be calculated according to the data in the table, as shown in Equations (16) and (17) :

$$u = \overline{\Delta T} = \frac{343+247+162+108+124+381+406+217}{8} = 248.5\,\text{min} \tag{16}$$

$$\sigma(\overline{\Delta T}) = \sqrt{\frac{(343-248.5)^2+(247-248.5)^2+...+(217-248.5)^2}{8}} = 108.98\,\text{min} \tag{17}$$

Substituting the calculated u and σ into equations (4) and (5), G and $G*$ can be calculated:

$$G = \frac{\sigma}{u} = 0.439 \tag{18}$$

$$G^* = \frac{\sigma}{u}\frac{1}{\sqrt{n}} = \frac{108.98}{248.5}\frac{1}{\sqrt{8}} = 0.155 \tag{19}$$

Through the same method above, G_0* before the implementation of assembly cell is calculated to be 0.582, while after the implementation of assembly cell, the value of $G*$ becomes 0.155. Combined with the previous analysis results, under the condition that the mean delivery deviation is positive, the smaller the value of $G*$, the stronger the ability of assembly cell to handle customer demand stably. Therefore, It can be explained that the implementation of assembly cell improves the ability of enterprises to deal with customer demands, and further shows that the assembly cell improves the flexibility of enterprises.

4.2 Calculation of efficiency index of assembly cell

In order to evaluate the overall efficiency of assembly cells, it can be seen from the previous analysis that the efficiency index of assembly cells is determined by calculating the OEE of key equipment.

According to the formula, the plan of key equipment and the actual calculation of OEE are shown in equations (20) and (21):

$$OEE_j = F_j I_j K_j = 80\% \times 80\% \times 95\% = 60.80\% \tag{20}$$

$$OEE = F I K = 76.46\% \times 70.22\% \times 98.10\% = 52.67\% \tag{21}$$

Then the efficiency coefficient of assembly cell is:

$$\varepsilon = \frac{OEE_j - OEE}{OEE} = \frac{60.80\% - 52.67\%}{52.67\%} = 0.15 \tag{22}$$

When the efficiency coefficient ε is positive, the lower the coefficient ε is, the higher the efficiency of the whole compressor blade flexible machining cell will be. According to the requirements of the enterprise, the difference between the planned efficiency and the actual efficiency should be within 10%, that is, ε should be less than 0.20. The efficiency coefficient obtained by calculation is 0.15, indicating that the overall efficiency of the assembly cell meets the requirements of the enterprise and the overall flexibility of the cell is relatively high.

4.3 Calculation of conversion cost index of assembly cell

Conversion cost is the cost of flexible state conversion of assembly cell in order to meet the changing market demand. This paper sorted out the relevant data of conversion costs by investigating enterprises, as shown in Table 2.

Table 2. Conversion cost data

Project	**Equipment (cell)**	**Number of people**	**Product category**	**Separate cost**	**Combined cost**
Plan	10	5	8	128753	87164
Actual	10	4	8	128753	86094

In the process of assembly cell flexibly responding to the changing external environment, the conversion cost coefficient C_1 of completing the combined product processing task is calculated as follows:

According to the data in Table 2, the conversion cost coefficient of compressor blade flexible processing cell to complete the processing of combined products in the order can be calculated under the state of external market demand constantly changing. By substituting the data into equations (10) to (12), the planned and actual equipment utilization coefficient and personnel utilization coefficient in this period can be calculated, as shown in Equations (23) to (26).

$$E_{1j} = \frac{Q_{1j}}{D_{1j}} = \frac{10}{8} = 1.25 \tag{23}$$

$$E_1 = \frac{Q_1}{D_1} = \frac{10}{8} = 1.25 \tag{24}$$

$$P_{1j} = \frac{J_{1j}}{D_{1j}} = \frac{5}{8} = 0.625 \tag{25}$$

$$P_1 = \frac{J_1}{D_1} = \frac{4}{8} = 0.5 \tag{26}$$

The calculated cost coefficients of planned and actual resource conversion during this period are shown in equations (27) and (28).

$$C_{1j} = E_{1j} \times P_{1j} = 1.25 \times 0.625 = 0.78 \tag{27}$$

$$C_1 = E_1 \times P_1 = 1.25 \times 0.5 = 0.625 \tag{28}$$

Then, the calculation of resource coefficient S in this period is shown in Equation (5.29) :

$$S = \frac{C_{1j} - C_1}{C_1} = 0.248 \tag{29}$$

The cost coefficient of process conversion of composite products completed flexibly by assembly cell is calculated as shown in Equation :

$$C_{2j} = \frac{C(L_1, L_2 ... L_n)_j}{C(L_1) + C(L_2) + ... + C(L_n)_j} = \frac{87164}{128753} = 0.677 \quad (30)$$

$$C_2 = \frac{C(L_1, L_2 ... L_n)}{C(L_1) + C(L_2) + ... + C(L_n)} = \frac{86094}{128753} = 0.669 \quad (31)$$

Then, the process coefficient Z is calculated as shown in Equation (32) :

$$Z = \frac{C_{2j} - C_2}{C_2} = \frac{0.677 - 0.669}{0.669} = 0.012 \quad (32)$$

The conversion cost coefficient C of assembly cell flexibility in producing composite products within a certain period is calculated as shown in Equation (5.33) :

$$C = \frac{S + Z}{2} = \frac{0.248 + 0.012}{2} = 0.13 \quad (33)$$

5. CONCLUSION

According to the above method, the conversion cost coefficient C before the assembly cell is implemented is -1.68, and after the processing cell is implemented, the value of C becomes 0.13. According to the previous analysis, if C is less than zero, it indicates that the actual cost of state transition is greater than the planned cost. If C is greater than zero, it means that the actual cost of the state transition is less than the planned cost. Thus, before the implementation of the assembly cell, the actual cost of completing the state transition is greater than the planned cost. After the introduction of the assembly cell, the value of the cost conversion coefficient C becomes positive, indicating that the actual cost of completing the state transition after the implementation of the flexible assembly cell is less than the planned cost, which further indicates that the assembly cell improves the flexibility of the enterprise.

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